Doc. #	TTCS-SYSU-AN-001-6.0		
Project	AMS-TTCS		
Title	**ACCUMULATOR THERMAL SAFETY ANALYSIS**		
Create Date	2009-11-18 18:10	**Save date**	2009-11-18 19:28
File name	TTCS-SYSU-AN-001-6.0_TTCS-Accumulator Thermal Safety Analysis.doc	**Issue**	6.0
Distribution	Unlimited	**Pages**	46

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5.0	*2007-10-30*	*Y.Chen*	*1. Redefine Two-Fault Failure for new electronic circuit.* *2. New simulations for New Accumulator TS-Saddle location, soldering method.* *3. Check the feasibility of 6 AHP-TSs.* *4. Check the accumulator's maximum nominal operation temperature for Accumulator TS.*
6.0		*J. van Es*	*1. Updated loop schematics* *2. Updated wire heater design* *3. Changed TS supplier (not Elmwood but Comepa)* *4. Added "old" Case 2 results for completeness* *5. Changed text details for better understanding* *6. Conclusions added with relation to safety analyses*

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1. SCOPE

This document presents the safety analysis of TTCS-Accumulator from the thermal point of view. The potential failures are hypothesized and evaluated here to verify the safety of the Accumulator-HP system.

The document starts with a general part describing the accumulator design, modeling and failure cases definition. The simulation result part is divided into two sections. One part concerns the safety analysis of the CO_2-accumulator. The second part describes the safety analysis of the accumulator heat pipe.

In both cases the design relies on Thermostates (TSs) switching off heat dissipating elements to avoid the accumulator and the AHP from being over heated. In order to give good insight in the safety of the design, the accumulator TS design is described and elucidated.

2. DOCUMENTS

2.1 References

Table 2-1 Reference list

Acronyms	Documents
RD1	TTCS accumulator safety issues, SYSU, ZH He, July 2006
RD2	AMSTR-NLR-TN-043_1.2_TTCS_Heater_specifications. SYSU/NLR/INFN, December 2005
RD3	ACC safety analysis_SYSU_051220, SYSU, ZC Huang, December 2005
RD4	AMSTR-NLR-TN-021, by T. Zwartbol 2004
RD5	TTCS-SYSU-AN-001-2.0_TTCS-Accumulator Thermal Safety Analysis, SYSU, Yue Chen/Z.H. He, December 2006
RD6	TTCS-SYSU-AN-001-3.0_TTCS-Accumulator Thermal Safety Analysis, SYSU, Yue Chen/Z.H. He, March 2007
RD7	TTCS-SYSU-AN-001-4.0_TTCS-Accumulator Thermal Safety Analysis, Y. Chen / J. van Es, April 2007
RD8	AMSTR-NLR-TN-044 issue 1.1, TTCS Safety Approach, October 2006, M. Bsibsi / J. van Es
RD9	AMSTR-NLR-TN-043 issue 1.3, TTCS heater specifications, September 2005, J. van Es / M. Bsibsi

2.2 Abbreviations and Acronyms

Table 2-2 Abbreviations and Acronyms

Abbreviations	Description
Accu	Accumulator
AHP/HP	Accumulator Heat Pipe
CH	Accumulator control heater
EH	Emergency Heater
HP	Heat pipe
TEC	Thermal Electronic Cooling (Peltier)
TS	Thermal Switch
TTCE	Tracker Thermal Control Electronics
TTCS	Tracker Thermal Control System
SST	Stainless steel

3. OBJECTIVE

The accumulator structure consists of two pressure vessels for the accumulator.

1) The Accumulator (Accu) vessel containing CO_2 is part of the TTCS CO_2 system. The TTCS cooling system has an MDP of 160 bars.
2) The Accumulator Heat Pipe (AHP) filled with ammonia. The AHP has an MDP of 50.2 Bars (MDT of 89^{o}C).

The objective of the presented simulations is to check whether the temperature safety requirements are met for the two pressure vessels.

For the CO_2 system it is shown that the accumulator stays below 55^{o}C as part of the TTCS safety approach described in AMSTR-NLR-TN-044 issue 1.0 October 2006 [RD-8]. For the ammonia filled Accumulator Heat Pipe (AHP) it is shown the temperature stays below the Maximum Design Temperature of 89^{o}C.

4. ACCUMULATOR AND HEAT PIPE DESIGN

4.1 Structure of the Accumulator

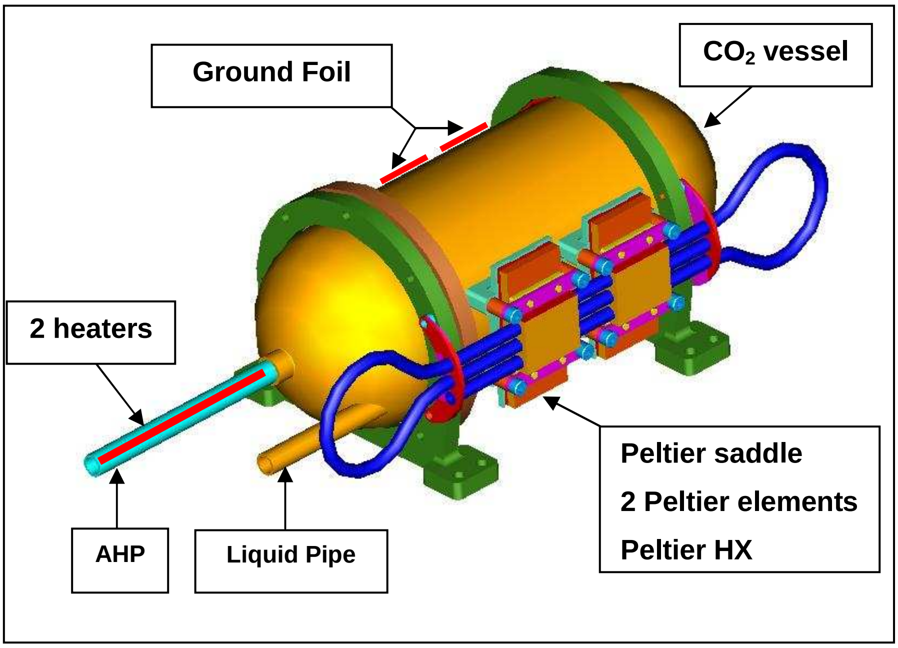


Figure 4-1 Structure of the TTCS Accumulator

The heat dissipating elements from the two redundant control system producing heat to the pressure vessels are:

1 Accumulator Heater (2×37.5W, one connected to TTCE A and one to B)

- Thermocoax wire heaters soldered to the AHP (see RD-8)

2 Peltier element (2×(2×25)=100W, one controlled Peltier (TEC) connected to TTCE A and one to B)

- One controlled Peltier (TEC) circuit consists of two Melcor CP 1.0-127-05 L 2 elements in series

3 Ground foil heater (2×44.6=89.2W, they are not connected to TTCE, used only in ground test)

4.2 Connection of wire heaters to the AHP

4.2.1 Control Heaters and Emergency Heaters

Table 4-1 Control Heaters and Emergency Heaters

	Diameter/mm	Length/mm	Resistance/Ohm*m^{-1}	Power Supply/V	Heat Load/W
Control Heater	**1.0**	**756**	**28**	**28**	**37.5**

4.2.2 Winding method Description

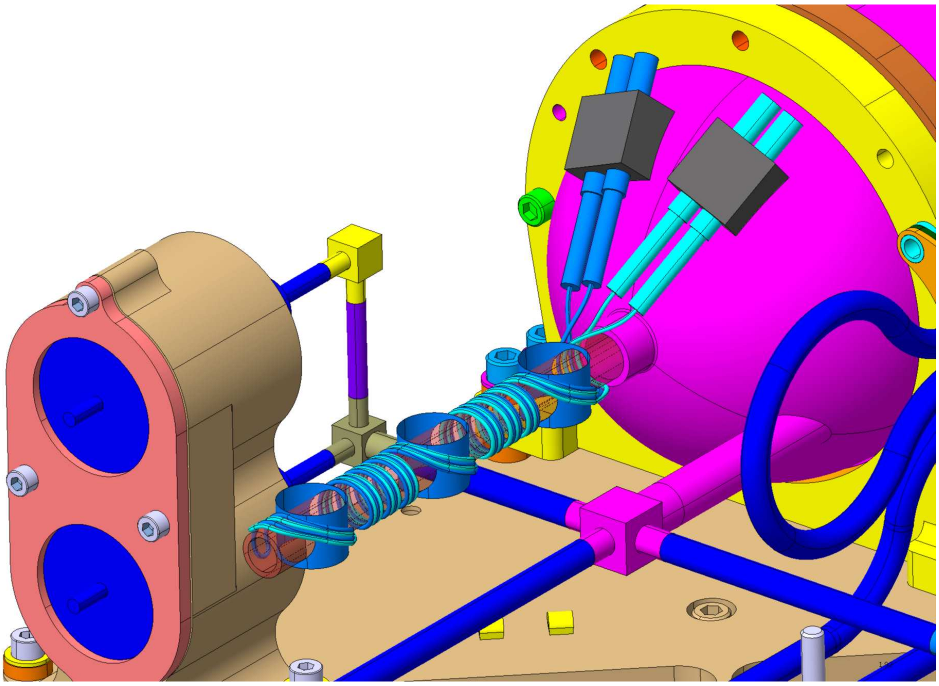


Figure 4-2 Manufacturing feasibility check of the wire heater connection to the AHP

In Figure 4-2, it is shown how the heaters will be attached to the AHP

- The heaters are doubled up as shown in enlargement (1) and in Figure 4-3;

Figure 4-3 Accumulator heaters configuration

More details on the heaters can be found in RD-6 and RD-8.

4.3 Location of Thermal Switches

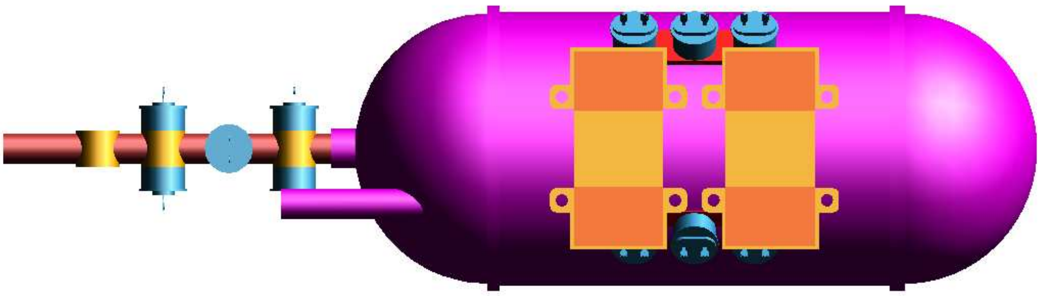


Figure 4-4 TS location on the accumulator and accumulator HP

For the Accumulator Heater and Emergency are in parallel to provide 37.5W, 2 TSs on the AHP are removed. (As Figure 4-4 b shown)

1) There are 6 TSs protecting the AHP, and they are assembled on 3 copper saddles, which are soldered to AHP directly. 1 copper saddle is left on AHP.
2) There are 6 Peltier TSs located on 2 thin copper saddle with 3 TSs on each saddle which is soldered to accumulator directly.

The feasibility of the above design will be proved in the following simulation and analysis.

4.4 Accumulator heaters electronics and TS lay-out

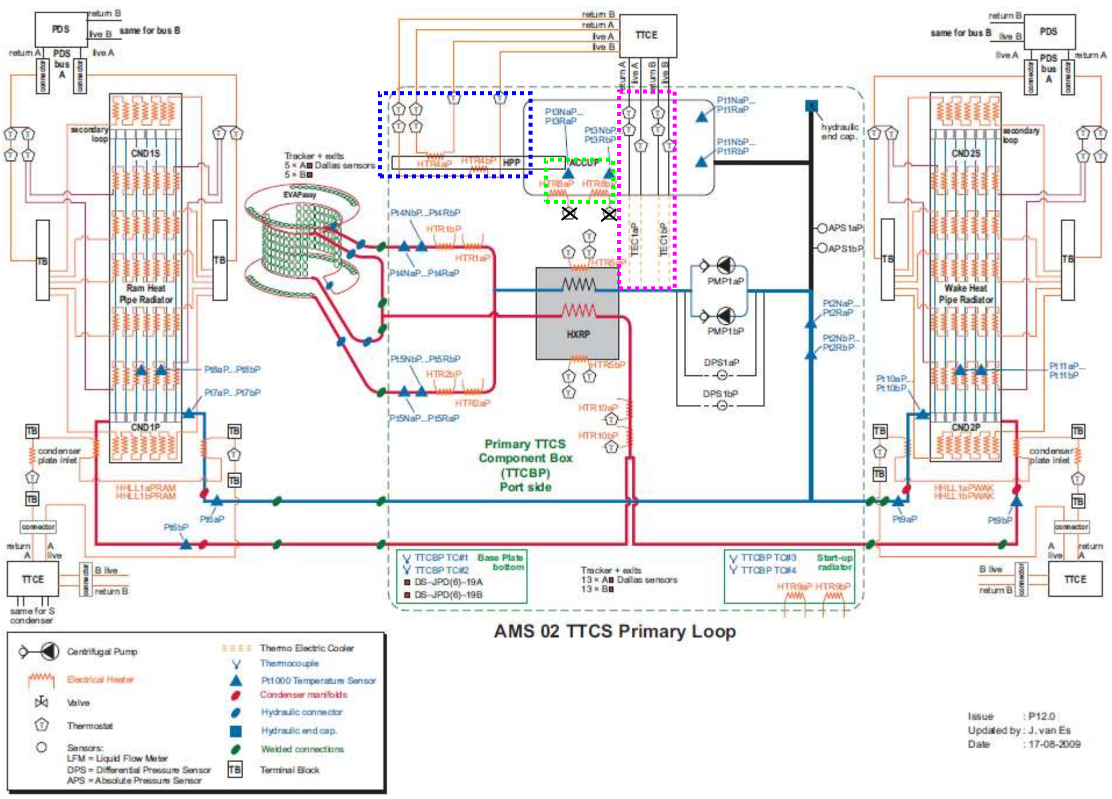


Figure 4-5 electronic schematic of TTCS Primary loop lay-out

In Figure 4-5, the electronic schematics of accumulator flight heaters, peltiers and ground test foils are shown (Refer to RD-2 for the ID#):

- As blue dashed frame indicated, there are two lines of heaters along AHP. Each line has two heaters (one is accumulator heater and the other is emergency heater), which are parallel connected. There are three TSs for each line of heaters, one TS is located in the heater feed line and two TSs in the return line. Every TS is able to switch off both heaters on its heater line.
- The peltiers electronic schematics are shown in magenta dashed frame. There are two TECs available for cooling the Accumulator. For each TEC, there are three TSs, which are all able to switch off the TEC on its circuit line.
- The ground foil heaters, shown in green dashed frame, are used in ground test.

All the simulations hereafter are based on the TSs configuration above, checking the feasibility of the TSs configuration upon the design. The simulations for primary and secondary box are the same.

5. THERMAL MODEL (TMG) DESCRIPTION

5.1 Structure

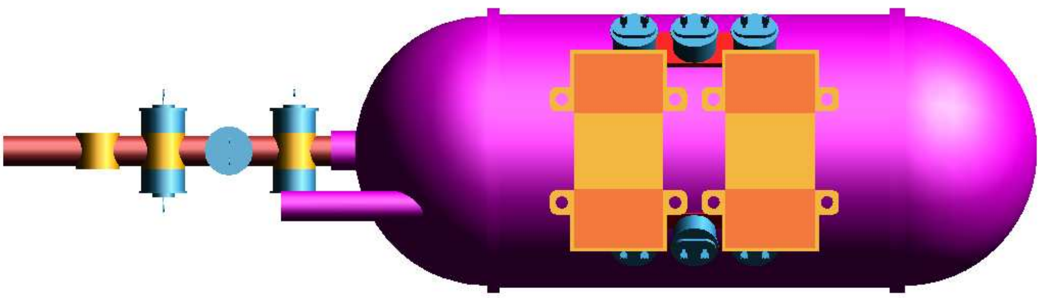


Figure 5-1 TS location on the accumulator and accumulator HP

For the Accumulator Heater and Emergency are in parallel to provide 37.5W, 2 TSs on the AHP are removed. (As Figure 4-4 b shown)

1) There are 6 TSs protecting the AHP, and they are assembled on 3 copper saddles, which are soldered to AHP directly. 1 copper saddle is left on AHP.
2) There are 6 Peltier TSs located on 2 thin copper saddle with 3 TSs on each saddle which is soldered to accumulator directly.

5.2 TMG Thermal Modeling

5.2.1 Introduction of I-deas/TMG

Simulation of this document is carried out by I-deas/TMG which is distributed by UGS. I-deas/TMG is an integrated module of “I-deas @ NX Series” which now called “NX MasterFEM TMG Thermal”. TMG can help you to carry out sophisticated thermal analysis on many heat transfer problems based on complex 3D geometry built by I-deas or any other software. But 3D geometry has no direct effect on the thermal analysis; only meshed FEM model (Finite Element Model) is taken into account for the thermal computations.

Types of conducting elements are supported by TMG when meshing FEM model:

- 3D elements (solid mesh)

- 2D elements (thin shell mesh)
- 1D elements (beam mesh)

5.2.2 TMG Modeling Description

As for complex model as accumulator-HP-Peltier-TS system, 3D elements are used mostly to mesh the whole system. Accumulator, HP, Peltier, TS and Saddles are meshed respectively by 3D elements (solid mesh). Small holes, screws and any other small details are cleaned to simplify the modeling. The whole system is at last built in one general FEM model which is shown in Figure 5-2. Material of every part is defined during the modeling meshing. Conductivity, density and specific heat are required in transient analysis while emissivity and absorptivity are also required if radiation is considered.

“Thermal Coupling” is frequently used to make a thermal link between different parts, e.g. the thermal conductance of Heaters and HP, the value of which is depended on the actual connecting method.

In a word, the generated heat is diffused by meshed elements and “thermal coupling” to the other parts. In transient analysis, the temperature will rise according to capacitance from a specific initial temperature.

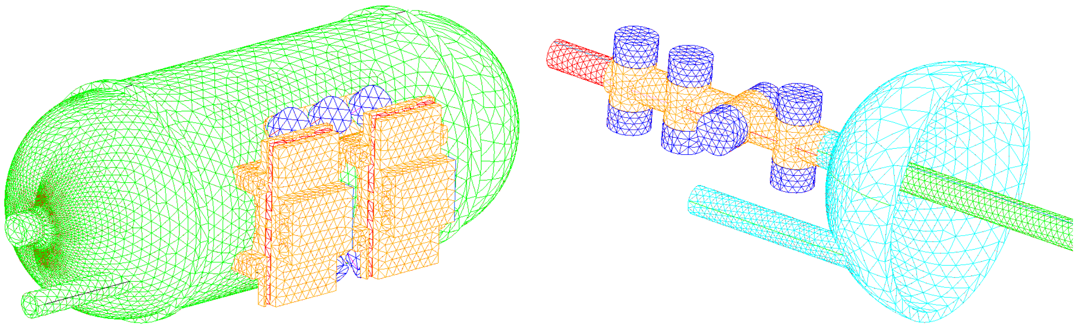


Figure 5-2 FEM (Finite Elements Model)

5.2.3 Material Properties

Table 5-1 Material properties of Accu-HP-TS system

Component	material	Thermal conductivity(W/mK)	Capacity(J/kgK)	Density(kg/m^3)
Accumulator	SST	16.3	500	8000
Heater	SST	16.3	500	8000
AHP	SST	16.3	500	8000
HX	Copper	380	386	8900
Peltier	Ceramic	20	1000	2000
Saddle	Copper	380	386	8900
TS	Aluminum	162	871	2600
Worked AHP	-	10000	500	8000

5.2.4 Thermostat

Table 5-2 Description of Thermostat

Type	**Comepa Model 45**
Temperature Range/^{o}C	38.3 – 93.3
Tolerance/ ^{o}C	+/- 2.8
Selected Switching Temperature/ ^{o}C AHP Selected Switching Temperature/ ^{o}C Peltier	55 45
Power Supply/VDC	28
Maximum Current/AMPS	5.0

5.2.5 Thermal Coupling

Table 5-3 Thermal Coefficient of Thermal Coupling

	AHP-Heater	Heater-Saddle	Saddle-TS	TS_Saddle-Accumulator
K /Wm^{-2}K^{-1}	3000	3000	8000	8000
	HP-Accu	Heater-Accu	CO_2-Accu	CO_2-AHP
K /Wm^{-2}K^{-1}	3000	3000	3000	3000

5.3 Monitored Fields of Model

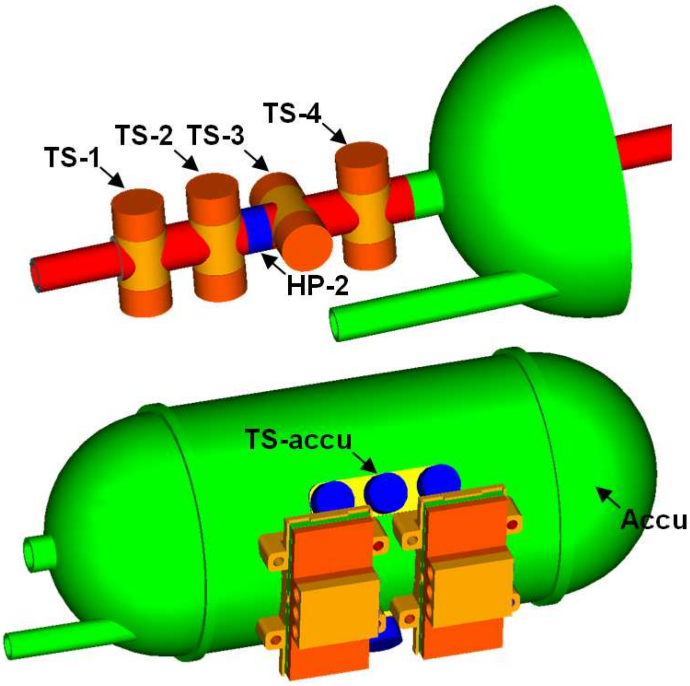
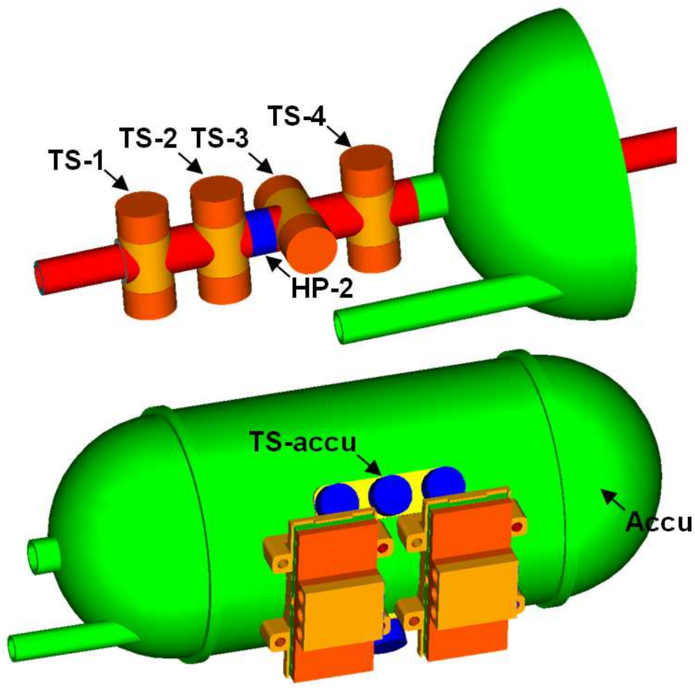


Figure 5-3 Monitored Points of Model



As

Figure 5-3 shown, the temperature shown below is the maximum temperature of the

"Monitored field".

- "HP-2" represents the maximum temperature of part of HP between TS-2 and TS-3.
- "TS-1" represents the maximum temperature of the 1st Thermal Switch.
- "TS-2" represents the maximum temperature of the 2st Thermal Switch.
- "TS-3" represents the maximum temperature of the 3st Thermal Switch.
- "TS-4" represents the maximum temperature of the 4st Thermal Switch.
- "HP_max" represents the maximum temperature of AHP.
- "Accu" represents the maximum temperature of part of Accumulator underneath the bottom of one Peltier-Saddle.

6. FAILURE CASE DEFINITOIN

6.1 Heating elements condition starting point

The starting point of the TTCS safety analysis is that all heaters and Peltier elements will be in the worst case possible condition. This worst case is defined as all A and B heaters and Peltier elements are switched on at full power.

By assuming this and showing a safe design discussion on TTCE control electronics operation or verification of embedded software is avoided.

6.2 Heat pipe failure

In case of an AHP Failure AHP can not conduct heat. In this case the AHP's thermal conductivity is put to zero.

6.3 CO_2 loss or CO_2 in supercritical condition

In case CO_2 is leaked off due to puncture or in case the CO_2 is in supercritical state the AHP does not have a heat sink into the CO_2 of the accumulator. The heat can therefore not conduct away from the AHP other than by conduction into the stainless steel vessel.

In this model case it is assumed the CO_2 in the accumulator has no thermal contact at all with the vessel wall (worst case).

6.4 TS failure

A TS failure means a TS does not switch-off the dissipating element and the heater is still dissipating its heat.

6.5 Non-operating pump

A working pump will provide cooling and is therefore only improving the safety cases.

6.6 Definition of two fault failure cases

In two fault failure, there are two hardware failures happen simultaneously. TTCE control failure is not included in two fault failure as it belongs to software failure. Based on the electronic schematic (Figure 4-5), the worst situation is all heating elements of A and B are at full power due to TTCE out of control.

Table 6-1 Two-Fault Failure List and Cases Definition

	AHP Failure	TS Failure
TS Failure	**Case 1:** **AHP Failure** **TS Failure**	**Case 4:** **Two TSs Failure** **Pump Stops**
CO_2 Loss/Supercritical	**Case 2:** **AHP Failure** **CO_2 Loss/Supercritical**	**Case 3:** **TS Failure** **CO2 Loss/Supercritical**

From Table 6-1, we can come to the following two-fault failure cases:

Case1: AHP Failure and TS Failure with 75W heat power and 100W Peltier power

TTCE out of control, all the heaters (including two Control Heaters and two Emergency Heaters) are powered on. The heating area is not uniform on AHP; and TS-3 or TS-4 is checked in this case.

With liquid/two-phase CO_2 serving as heat sink, the accumulator will not be over heated even all the TEC heating elements are running at full power. This will be checked in this case.

Two Fault Failures:

- AHP Failure

- One TS Failure

Case2: AHP Failure and CO_2 loss/Supercritical with 75W heater power and 100W Peltier power

TTCE out of control, all the heaters (including two Control Heaters and two Emergency Heaters) are powered on. The heating area is not uniform on AHP, and TS-3 is checked in this case.

As CO_2 loss or be in supercritical state in this case, CO_2 is not an efficient heat sink, but 100W TECs are still working due to TTCE Failure, the Accumulator TS is checked in this case.

Two Fault Failures:

- AHP Failure
- CO_2 Loss

Case3: CO_2 Loss/Supercritical and TS Failure with 75W heater power and 100W Peltier power

TTCE out of control, all the heaters (including two Control Heaters and two Emergency Heaters) are powered on. The heating area is not uniform on AHP. Based on RD-7's results, TS-3 is the first TS reaching switching temperature if no TS failed. If TS-3 is failure, TS-4 is checked in this case.

As CO_2 loss or be in supercritical state in this case, CO_2 is not an efficient heat sink, but 100W TECs are still working due to TTCE Failure, the Accumulator TS is checked in this case.

Two Fault Failures:

- CO_2 Loss
- One TS Failure

Case4: Two TSs Failure with 75W heater power and 100W Peltier power when pump stops

TTCE out of control, all the heaters (including two Control Heaters and two Emergency Heaters) and TECs are powered on. The temperature along AHP is almost uniform since AHP works normally, all AHP TSs can protect AHP from being over heated. But, it is still necessary to have at least 3 TSs for protecting AHP, to get through the situation that two AHP TSs failed at the same time, which is checked in this case.

In this case, if pump stops, the overheated CO_2 by 100W Peltier. This is similar to CO_2 Loss/Supercritical state. The Accumulator TS is checked in this case.

Two Fault Failures:

- One TS Failure
- Another TS Failure

7. MODELING RESULTS CO_2-ACCUMULATOR SAFETY

7.1 Case1: AHP Failure and TS Failure with Heat Sink

CO_2 in the accumulator works as a heat sink. This case is going to check that, with CO_2 inside the accumulator serving as heat sink, the accumulator will be safe even all TECs run at full power.

7.1.1 Boundary

Initial Temperature: T_{ini} = -20^{o}C

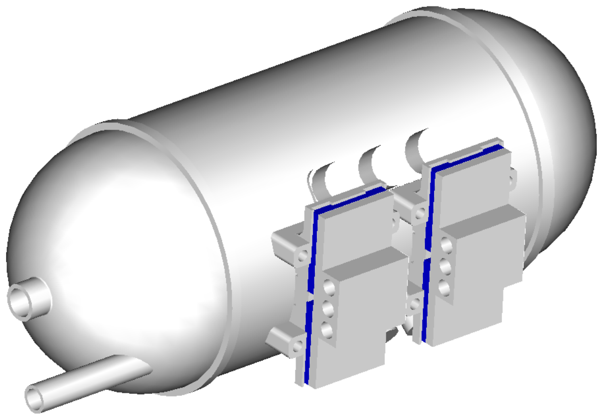


Figure 7-1 Boundary Description of Case1

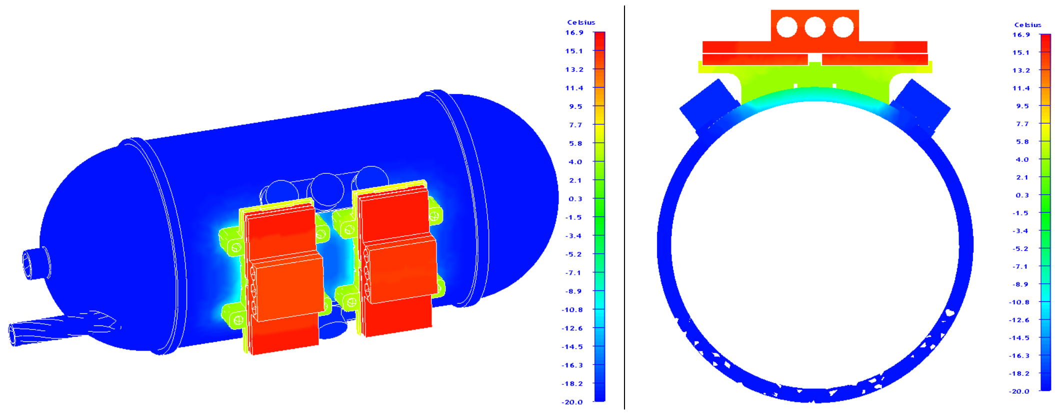
Table 7-1 Boundary Condition of Case1

	Highlighted	Heat Load/W
Peltiers	Blue	100
Heat Sink	-	T_{co_2}= -20°C

PS:

a) T_{co_2} is a constant, which means that the CO_2 is working at -20°C.

7.1.2 Simulation Results



(a) (b)

Figure 7-2 Temperature contour at maximum temperature in Case1 when all TSs functioning normally

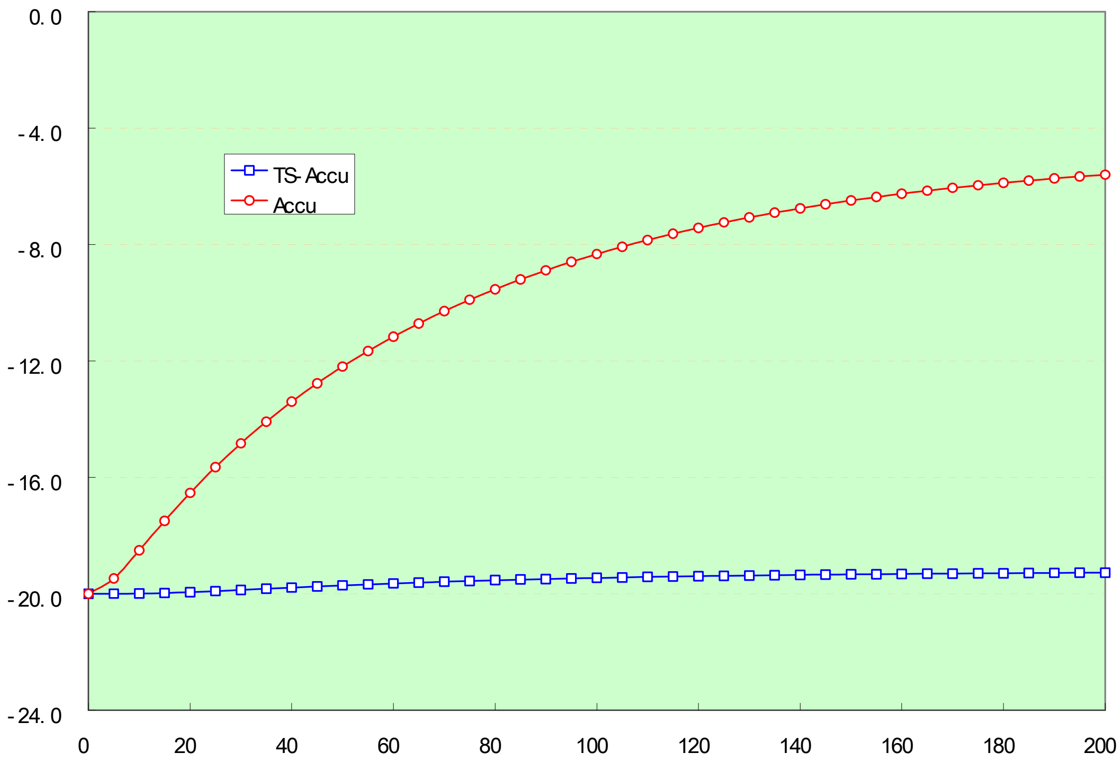
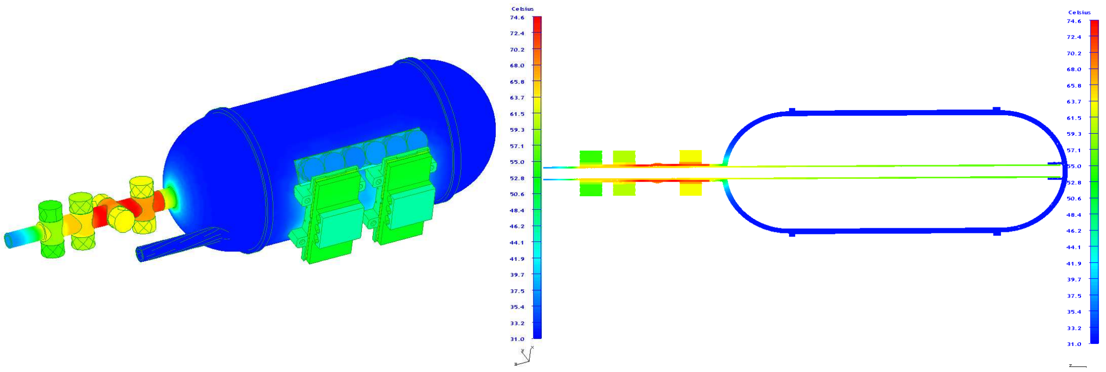


Figure 7-3 Temperature of Accumulator, AHP and Thermostats in Case1

If CO_2 is still an efficient heat sink, it is clear that the CO_2 inside the accumulator will stay below 55^{o}C even with the 100W Peltiers operating. Due to the HP failure the additional heat from the AHP heaters into the accumulator is limited. All AHP TSs switch off the heaters well before CO_2 becomes even close to 55°C. As TS failures are only important for the AHP safety the individual TS safety failures are only discussed in section 8.

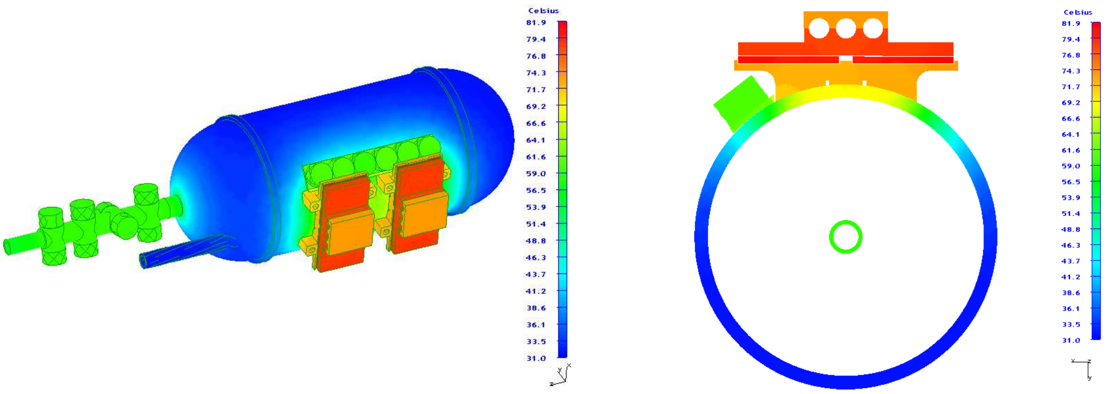
7.2 Case 2: AHP failure and CO_2 Loss/Supercritical

A simulation has been performed when HP TS's placement was not updated. When TS's placement changed, the maximum temperature of HP is lower. So, the final results will be better.



(a) (b)

Figure 7-4 Temperature Contour when t=45s



(a) (b)

Figure 7-5 Temperature Contour when t=135s

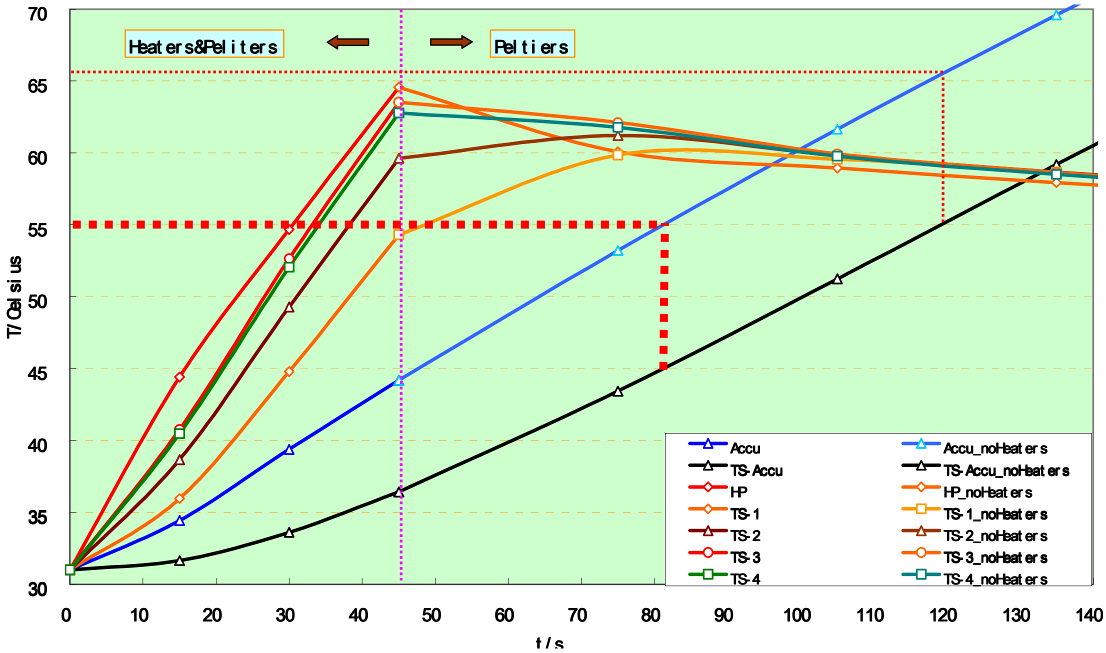


Figure 7-6 Temperature versus time for AHP worked, CO2 Gone Failure with TTCE Out of Control

Base on the above results, the HP will be safe, and the maximum temperature of Accu can be kept at about 55C by Accu-TSs.

Based on above results the Accumulator TS switching point (at peltier) was set to +45 C to keep the accumulator below +55 C. Which is consistent with the TTCS safety approach.

7.3 Case3: CO_2 Loss/Supercritical and TS Failure without Heat Sink

7.3.1 Boundary

Initial Temperature: T_{ini}=31°C.

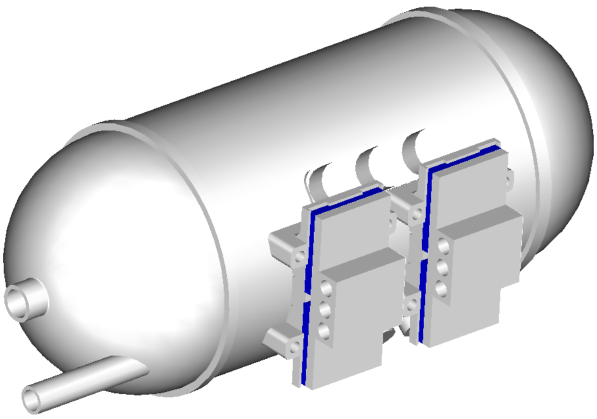


Figure 7-7 Boundary Description of Case3

Table 7-2 Boundary Condition of Case3

	Highlighted	Heat Load/W
Peltiers	Blue	100
Heat Sink	-	**Null**

7.3.2 Simulation Results

- Case3: CO2 supercritical and AHP failure

By two-fold failure definition, all the TSs function normally in this case. The temperature of HP can be effectively control by HP-TSs. On Peltiers' side, Accu-TSs will monitor the Accu's temperature to keep the accumulator below Maximum Design Temperature (MDT).

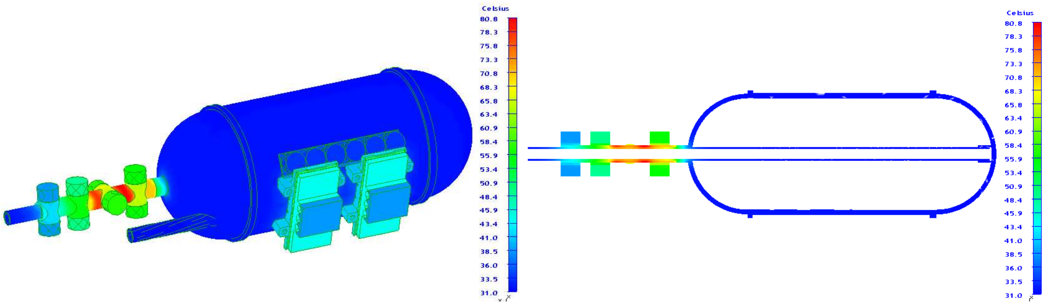


Figure 7-8 Temperature Contour when t=25s

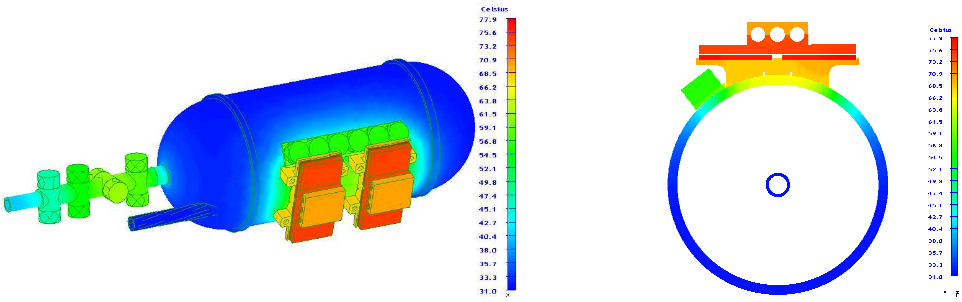


Figure 7-9 Temperature Contour when t=120s

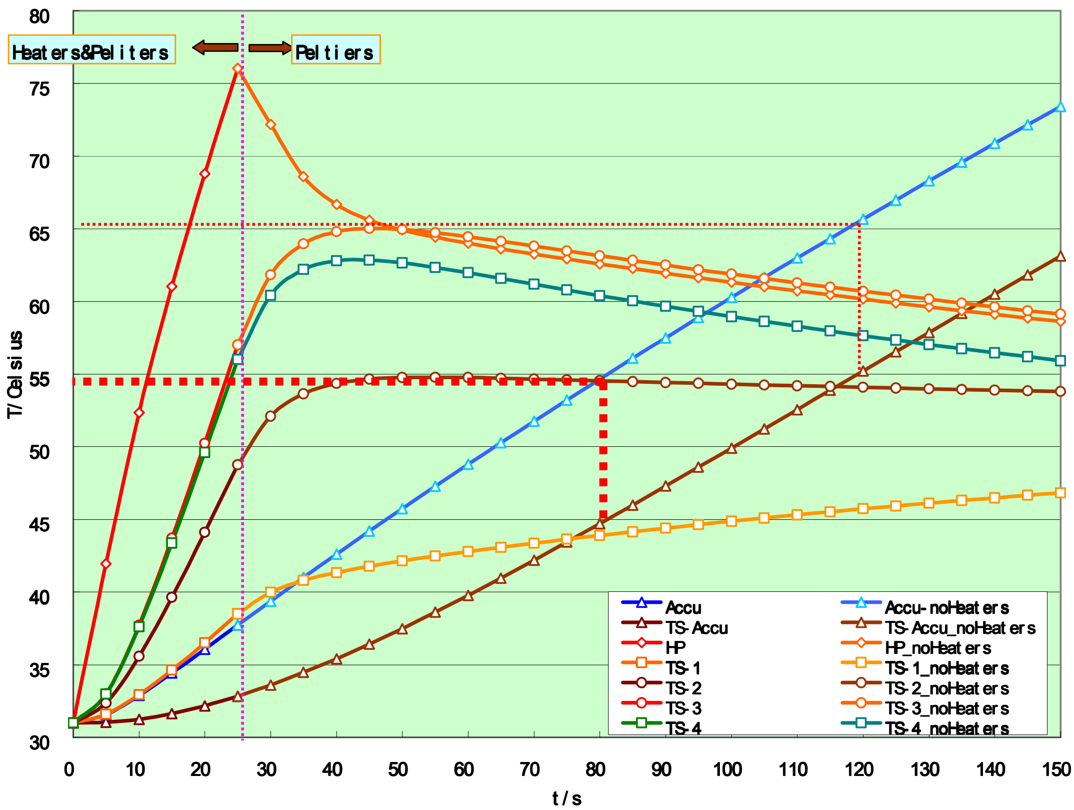


Figure 7-10 Temperature versus time for AHP Failure, CO_2 Gone Failure with TTCE Out of Control

Base on the above results the maximum Accu temperature switch off at about 55C by the Accu-TSs when the TS switch temperature is set to +45 C. All all three TS per Peltier are contacted on the same copper block no difference for the different TS is found.

7.4 Maximum Nominal Operation Temperature

In this case, a maximum temperature is simulated for nominal operation.

Since the possible loop temperature variations is from -20^{o}C to 20^{o}C. So, the initial temperature of the simulation is set as 20^{o}C. This is nominal running, the heat generated by the AHP can successfully brought away by the CO_2, keeping the temperature of the CO_2 as 20^{o}C.

7.4.1 Boundary

Initial Temperature: T_{ini}=31°C.

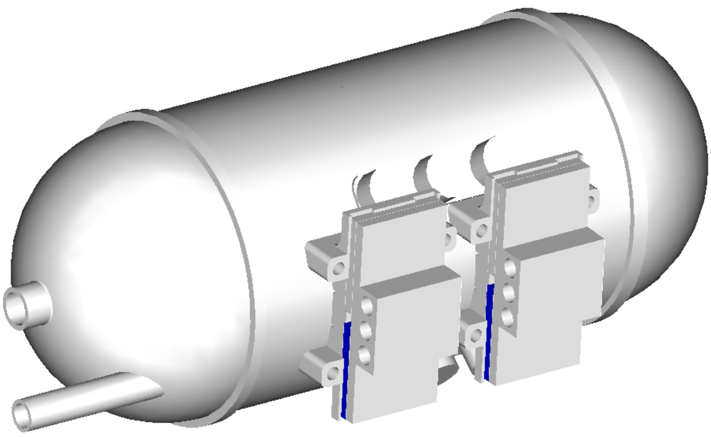
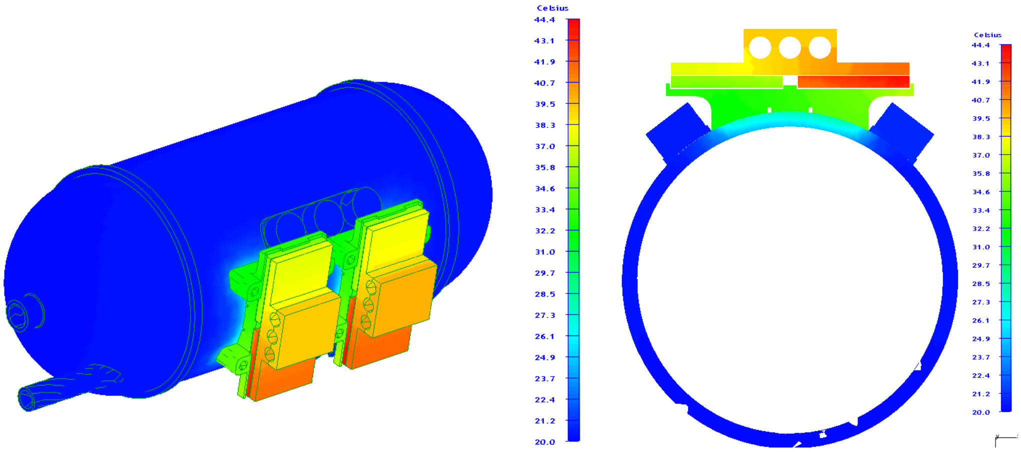


Figure 7-11 Boundary Description of nominal case

Table 7-3 Boundary Condition of nominal case

	Highlighted	Heat Load/W
Peltiers	Blue	50
Heat Sink	-	**Null**

7.4.2 Simulation Results



(a) (b)

Figure 7-12 Temperature contour of nominal case

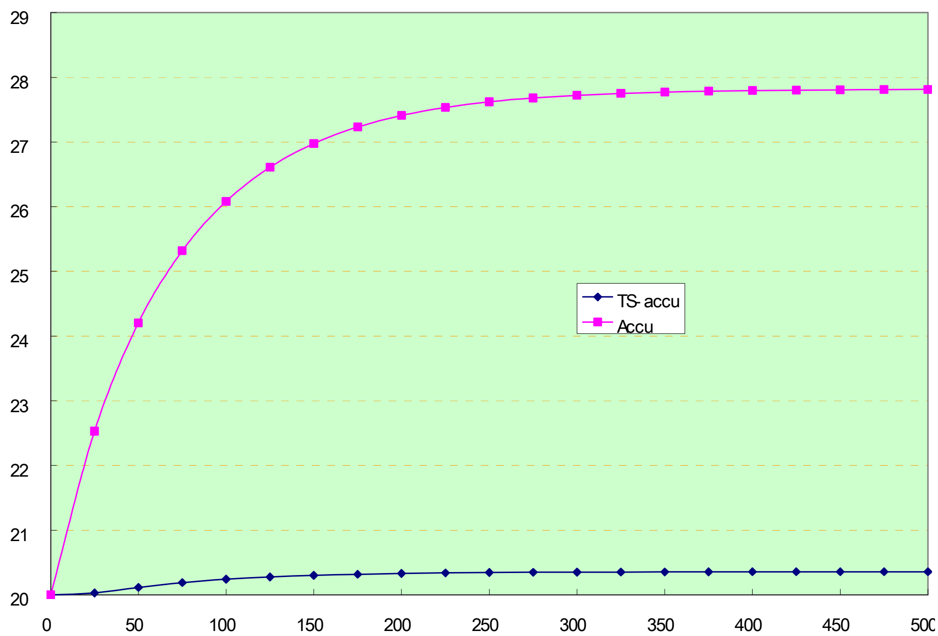


Figure 7-13 Temperature of Accumulator, AHP and Thermostats in nominal case

From **Error! Reference source not found.**, the temperature of the accumulator will come to 28°C, when the heat of the Peltiers can not be brought away by the running loop. In reality, the accumulator is cooled by the Peltier, while the running loop is cooling the heat part of the Peltiers. So, the temperature of the accumulator is lower than 28°C. To avoid switching off during normal operation, the Accu TS switch temperature should be choosen higher than 28°C.

8. MODELING RESULTS AHP SAFETY

8.1 Case1: AHP Failure and TS Failure

Here, AHP is failed and all the heaters are switched on. The second failure is a TS failure.

8.1.1 Initial Temperature Definition for Failed AHP

1) Analysis

For failed AHP: here we define different initial temperature as different cases. In the below figure, take HP-3 and TS-3 of every initial temperature as examples; compare these two curves of each case in one graph.

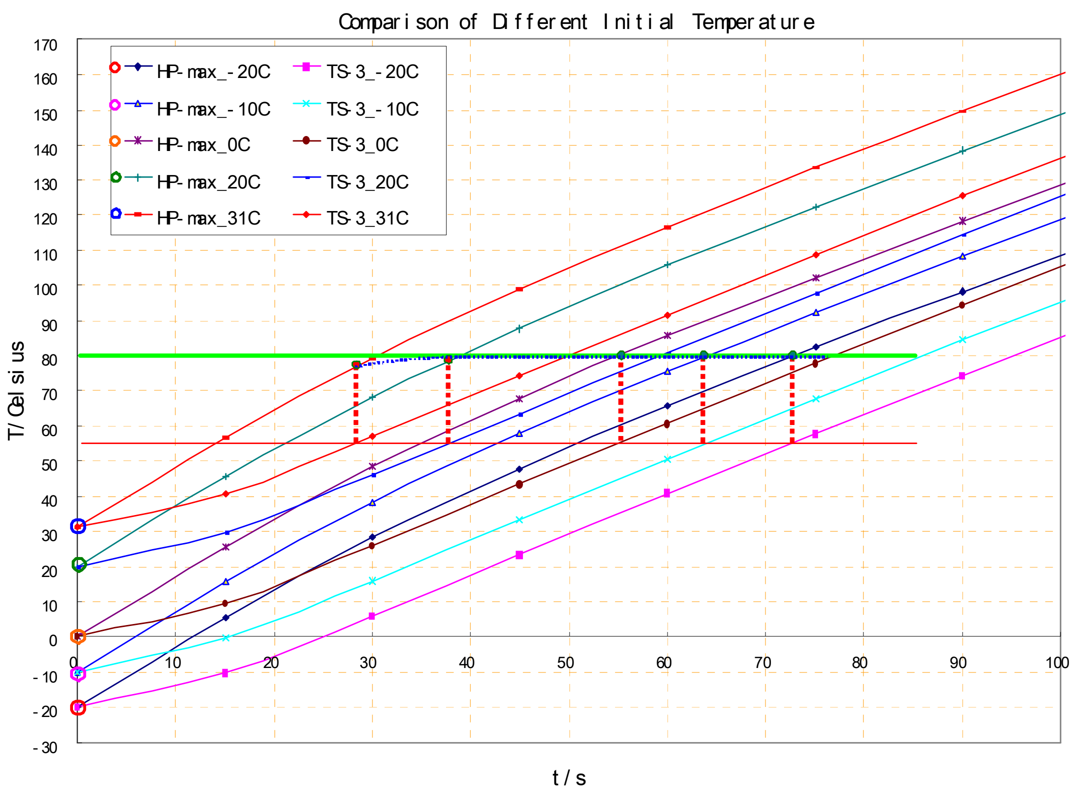


Figure 8-1 Comparison of different Initial Temperature for Failed AHP

● and ●: the temperature of HP-3 when TS-2 comes to 55°C

TS-3 switches at 55°C, and it versus to a temperature of HP-3, which is shown as ● or ●. For low initial temperatures, e.g. in Case_-20°C, Case_-10°C, and Case_0°C, when TS-3 switches, HP-3's temperature is the same (all on the green line). For high initial temperature, e.g. in Case_31°C, Case_20°C, when TS-3 switches, HP-3's temperature is lower than the green line.

To check whether the model can meet the criterion in the worst case, the low initial temperature (Case_-20°C) is selected as the representative initial temperature for the Failed AHP cases, because the temperature of HP-3 is the highest when TS-3 switches. If Case_-20°C meets the criterion, other initial temperature will also pass.

2) Initial Temperature for Failed AHP cases

$T_{ini} = -20^{o}C$

8.1.2 Boundary

Initial Temperature: T_{ini}=-20°C.

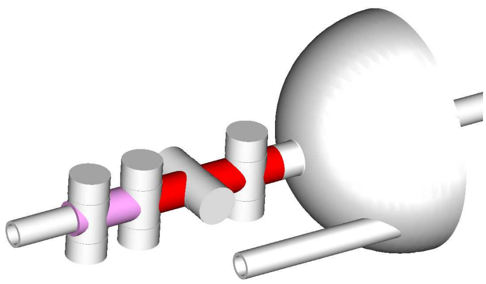


Figure 8-2 Boundary Description of Case1

Table 8-1 Boundary Condition of Case1 when TS-3 failed

	Highlighted	Heat Load/W	
Heaters (Total=2×15+2×22.5=75W)	Red	Before TS-4 switches	**64.9=22.5*2+15*2*56.7/85.5**
		After TS-4 switches	**19.9=15*2*56.7/85.5**
	Pink	Before TS-4 switches	**10.1**
		After TS-4	**10.1**

		switches	
Heat Sink	-	Tco_2= -20°C	

PS:

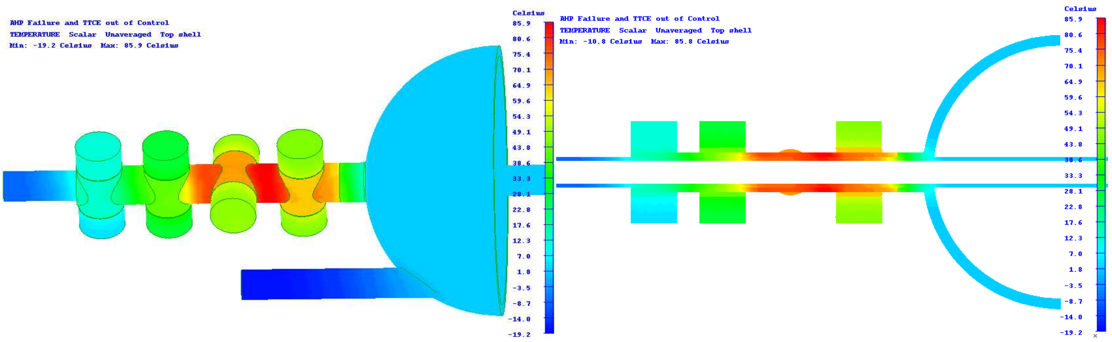
a) As Control Heater is shorter, so its heating area is only the “Red Part” while the Emergency Heater’s heating area is “Red part + Pink part”.

b) CO_2 is working at -20°C, and Tco_2 is a constant.

c) The “covering-length” of Control Heater is 56.7mm

d) Based on the electronic schematic (Figure 4-5), when TS-4 switches, heat-load on AHP is zero in reality.

8.1.3 Simulation Results



(a) (b)

Figure 8-3 Temperature Contour of Case1 when maximum temperature is 85.9°C

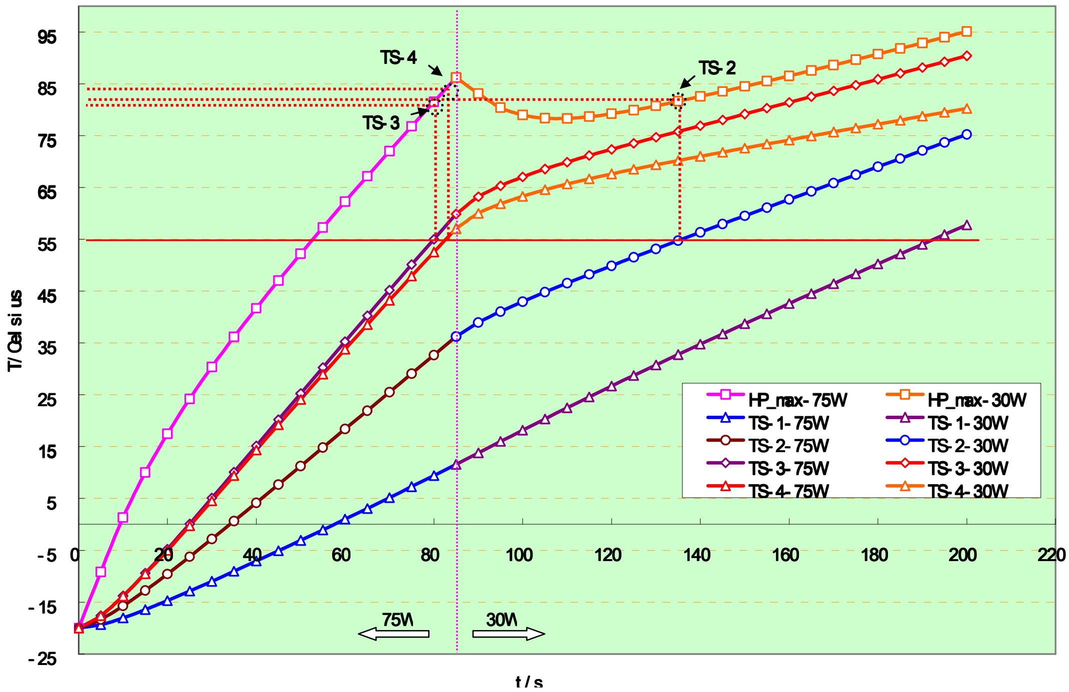


Figure 8-4 Temperatures of AHP and Thermal Switches in Case1

- If TS-3 runs normally in the whole process, The TS-3 can switches off all the heaters when the maximum temperature of AHP is only 80°C.
- If TS-3 is failed, TS-4 can switch off all the heaters, and the maximum temperature of AHP is about 85°C.

8.2 Case2: AHP Failure and CO_2 Loss/Supercritical

8.2.1 Boundary

Initial Temperature: T_{ini}=-20°C.

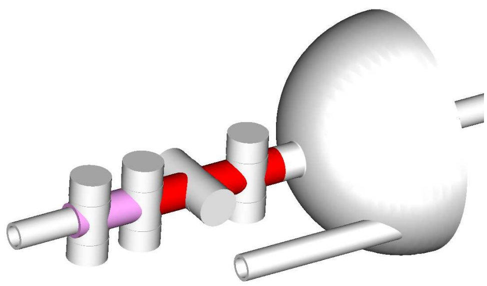


Figure 8-5 Boundary Description of Case2

Table 8-2 Boundary Condition of Case2

	Highlighted	Heat Load/W	
Heaters (Total=2×15+2×22.5=75W)	Red	Before TS-3 switches	**64.9=22.5*2+15*2*56.7/85.5**
		After TS-3 switches	**19.9=15*2*56.7/85.5**
	Pink	Before TS-3 switches	**10.1**
		After TS-3 switches	**10.1**
Heat Sink	-	**Null**	

PS:

a) As Control Heater is shorter, so its heating area is only the “Red Part” while the Emergency Heater’s heating area is “Red part + Pink part”.

b) The “covering-length” of Control Heater is 56.7mm.

c) Based on the electronic schematic (Figure 4-5), when TS-3 switches, heat-load on AHP is zero in reality.

8.2.2 Simulation Results

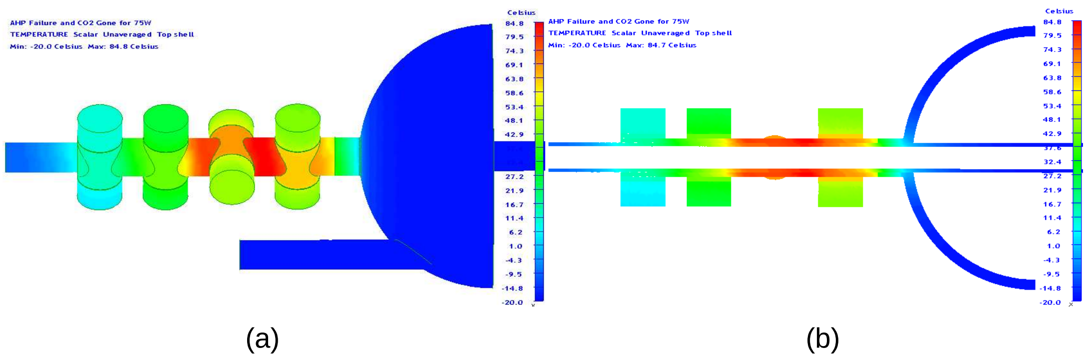


Figure 8-6 Temperature Contour of Case2 when maximum temperature is 84.8°C

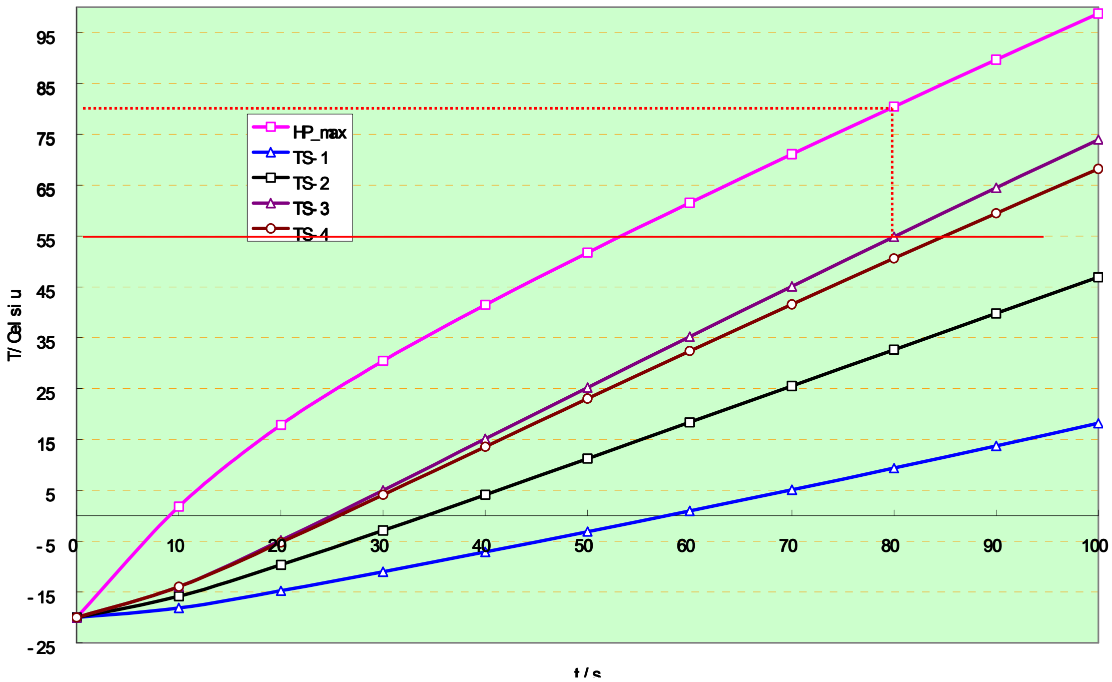


Figure 8-7 Temperatures of AHP and Thermal Switches in Case2

As shown in Figure 8-7, the result is almost the same as Case1 if TS-3 functions normally, this is because the thermal diffusivity of SST is very poor. The heat sink on the SST can not help to dump the heat quickly. The first switching TS is TS-3, and the Maximum temperature of AHP is 75°C.

8.3 Case3: CO_2 Loss/Supercritical and a TS Failure

TTCE is out of control, so all the heaters are switched on. AHP works normally.

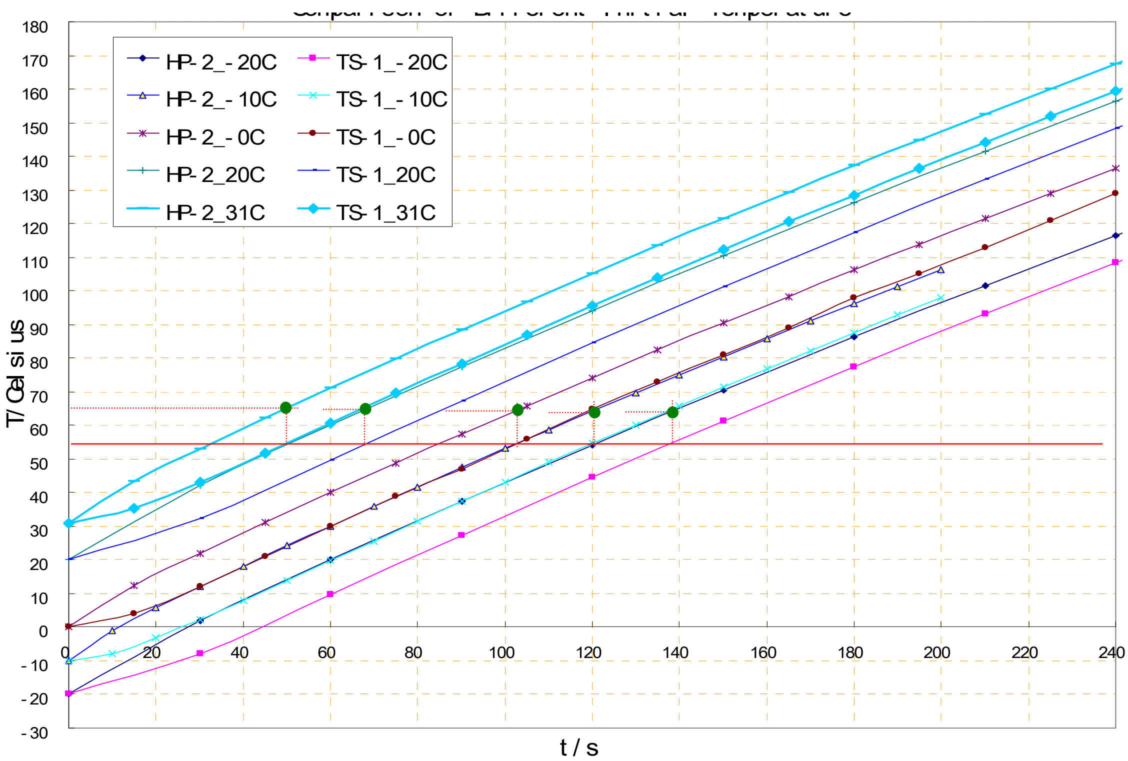
CO_2 is loss or supercritical, so there' no heat sink in this case.

8.3.1 Initial Temperature Definition for Normal AHP

1) Analysis

For normal AHP, the temperature rising characteristic is different from Failed AHP when heated.

Here we define different initial temperature as different cases. In Figure 8-8, take HP-2 and TS-1 of every initial temperature case as examples; compare these two curves of each case in one graph.



● the temperature of HP-3 when TS-2 comes to 40°C

Figure 8-8 Comparison of different initial temperature of Normal AHP

When TS-1 switches at 55°C in every case, the temperature of HP-2 is marked in Figure 8-8 as ●. Compare the different ● of every case, we can find that they are almost at the same horizontal line of 66°C. In fact, the temperature of HP-2 in Case_31°C is the highest when TS-1 switches. If Case_31°C meets the criterion, so do the other initial temperature cases.

Initial temperature for Normal AHP cases:

T_{ini}= 31°C

8.3.2 Boundary

Initial Temperature: T_{ini}=31°C.

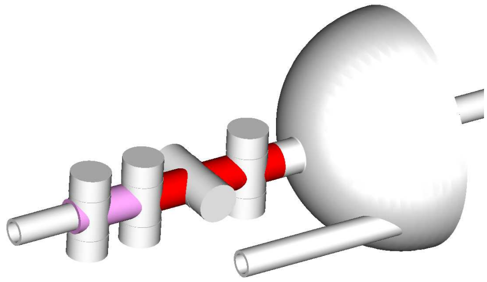


Figure 8-9 Boundary Description of Case3

Table 8-3 Boundary Condition of Case3

	Highlighted	Heat Load/W	
Heaters (Total=2×37.5=75W)	Red	Before TS-4 switches	**64.9=22.5*2+15*2*56.7/85.5**
		After TS-4 switches	**19.9=15*2*56.7/85.5**
	Pink	Before TS-4 switches	**10.1**
		After TS-4 switches	**10.1**
Heat Sink	-	**Null**	

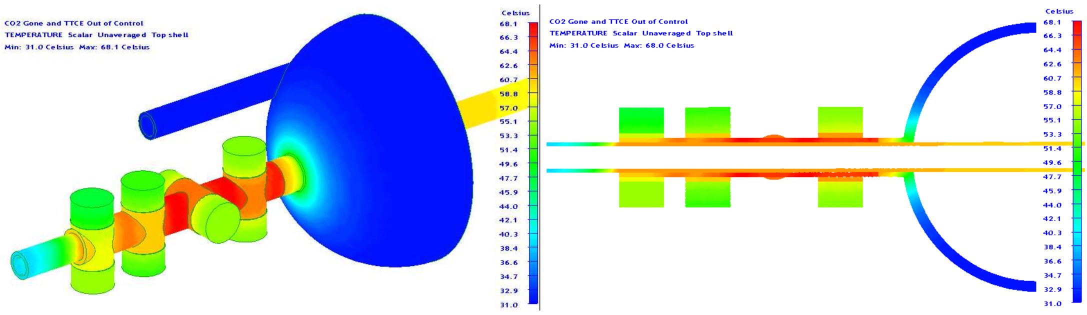
PS:

a) As Control Heater is shorter, so its heating area is only the “Red Part” while the Emergency Heater’s heating area is “Red part + Pink part”.

b) The “covering-length” of Control Heater is 56.7mm.

c) Based on the electronic schematic (Figure 4-5), when TS-3 switches, heat-load on AHP is zero in reality.

8.3.3 Simulation Results



(a) (b)

Figure 8-10 Temperature Contour of Case3 when maximum temperature is 68.1°C

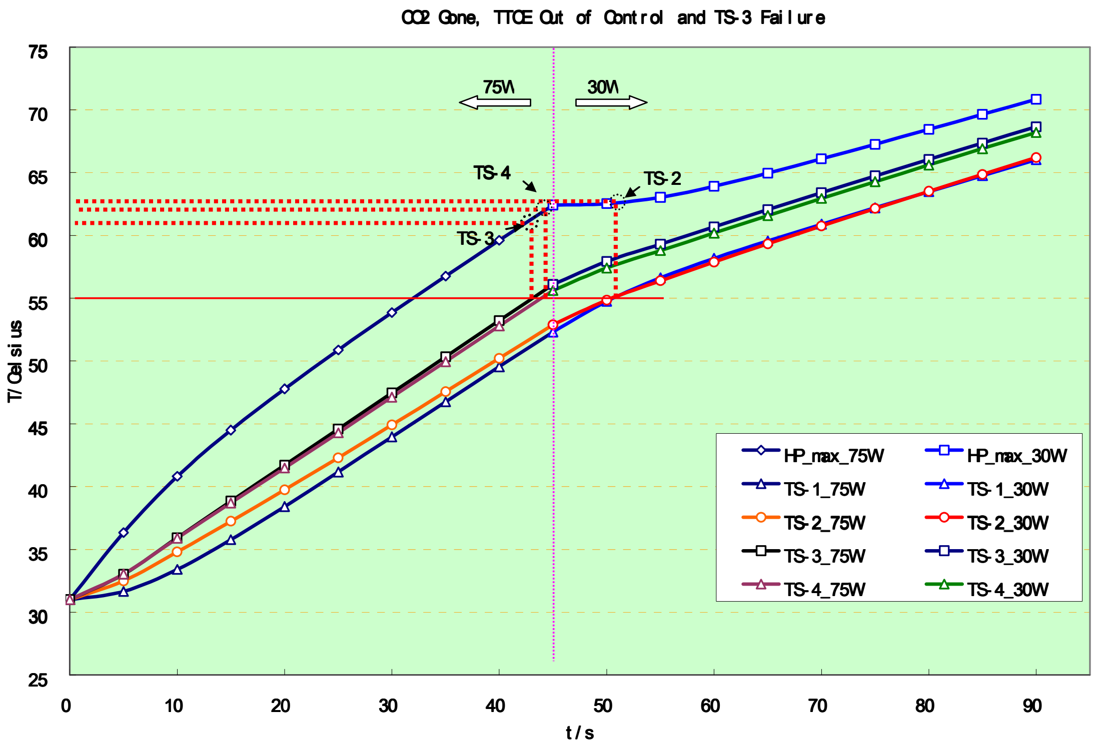


Figure 8-11 Temperatures of AHP and Thermal Switches in Case3

- If TS-3 runs normally in the whole process, The TS-3 can switches off all the heaters when the maximum temperature of AHP is only 61°C.
- If TS-3 is failed, TS-4 can switch off all the heaters, and the maximum temperature of AHP is about 64°C.

8.4 Case4: Two TSs Failure when Pump Stops

TTCE is out of control, so all the heaters are switched on. AHP works normally; the temperature of AHP is almost uniform.

8.4.1 Boundary

There is no heat sink in this case.

Initial Temperature: T_{ini}=31°C.

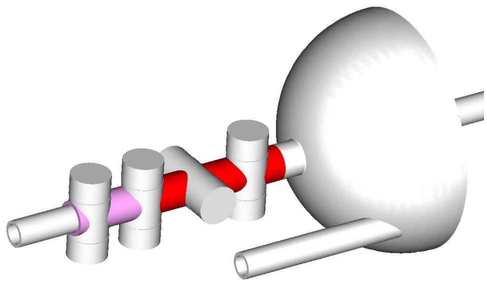


Figure 8-12 Boundary Description of Case4

Table 8-4 Boundary Condition of Case4

	Highlighted	Heat Load/W
Heaters (Total=2×15+2×22.5=75W)	Red	**64.9=22.5*2+15*2*56.7/85.5**
	Pink	**10.1**
Heat Sink	-	**Null**

PS:

a) As Control Heater is shorter, so its heating area is only the “Red Part” while the Emergency Heater’s heating area is “Red part + Pink part”.

b) The “covering-length” of Control Heater is 56.7mm.

8.4.2 Simulation Results

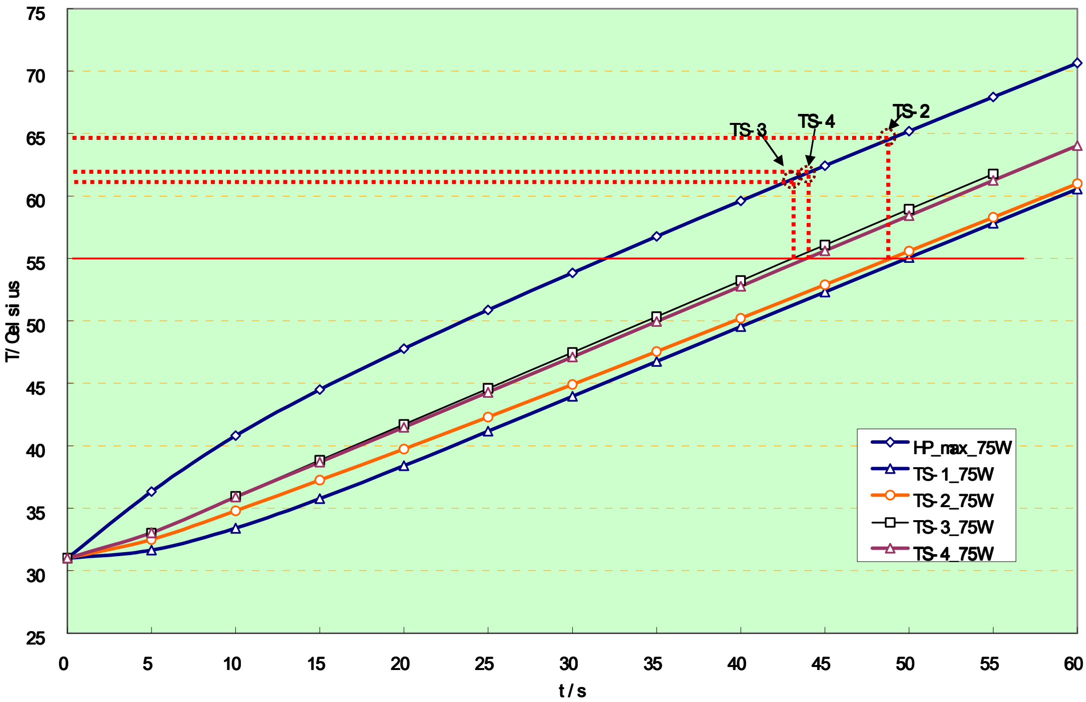


Figure 8-13 Temperatures of AHP and Thermal Switches in Case4

As shown in Figure 8-13, even TS-3 and TS-4 failed at the same time, TS-2 can still protect the AHP. The maximum temperature of AHP is 65^{o}C when TS-2 switches.

8.5 Case5: Normal Running

The system operates normally in this case.

8.5.1 Boundary Condition

Initial Temperature: T_{ini}=20°C.

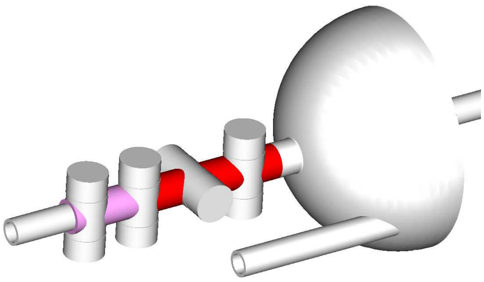


Figure 8-14 Boundary Description of Case5

Table 8-5 Boundary Condition of Case5

	Highlighted	Heat Load/W
Heaters (Total=15W+22.5W=37.5W)	Red	**32.45=22.5+15*56.7/85.5**
	Pink	**5.05=37.5-32.45**
Heat Sink	-	**T_{CO_2}= 20°C**

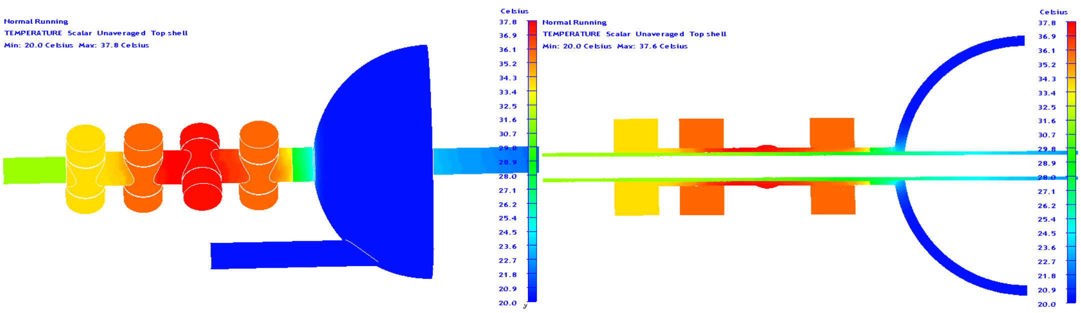
PS:

a) As Control Heater is shorter, so its heating area is only the “Red Part” while the Emergency Heater’s heating area is “Red part + Pink part”.

b) CO_2 is working at 20°C, and T_{CO_2} is a constant.

c) The “covering-length” of Control Heater is 56.7mm.

8.5.2 Simulation Results



(a) (b)

Figure 8-15 Temperature Contour of Case5 when maximum temperature is 37.8°C

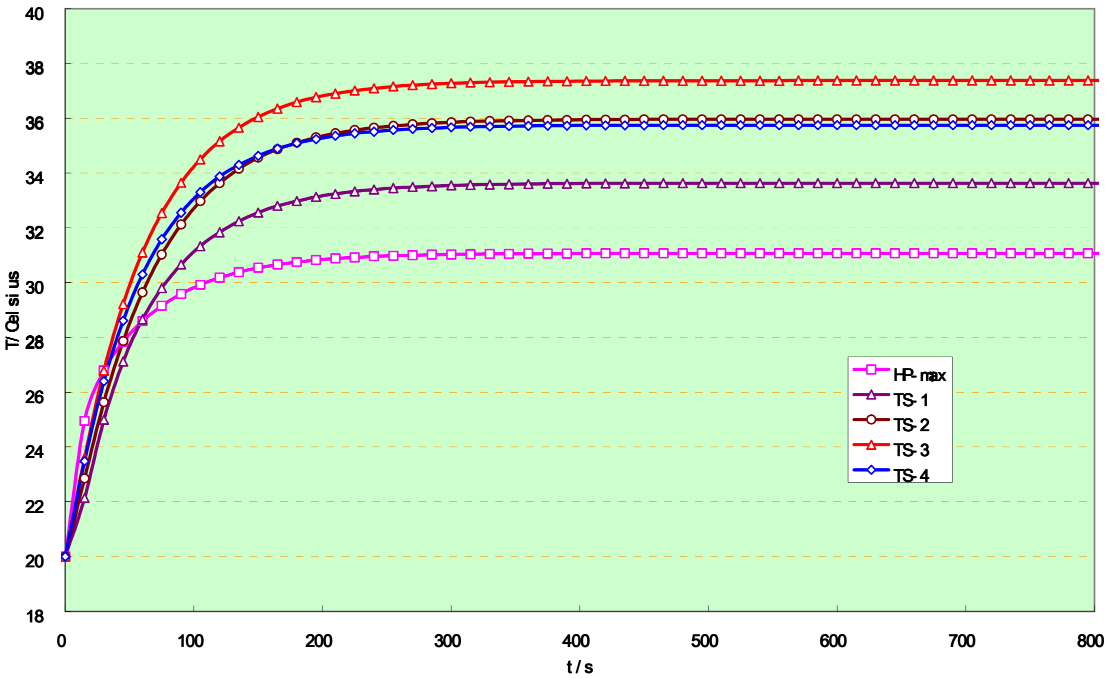


Figure 8-16 Temperatures of AHP and Thermal Switches in Case5

- The system will come to a steady-state in the end, and the temperature is in the range of 30°C and 38°C.

9. SUMMARY

Table 9-1 Summarized temperatures of the AHP and the Accumulator when TSs switch

Case	Description	Switching TS	AHP_{max}/°C	$Accu_{max}$/°C
Case1	AHP Fully Failure; TS-3 Failure Heat Load: $Heaters_{\_HP}$ = 75W; Peltiers = 100W $T_{initial}$ = -20°C T_{CO2} = -20°C	TS-4	85	-
		-	-	-6 (Steady-State)
Case2	AHP Failure; CO2 Gone/Supercritical Heat Load: $Heaters_{\_HP}$ = 75W; Peltiers = 100W $T_{initial}$ = -20°C	TS-3	80	-
		TS_{-TEC}	-	55
Case3	CO2 Gone/Supercritical; TS-3 Failure Heat Load: $Heaters_{\_HP}$ = 75W; Peltiers = 100W $T_{initial}$ = 31°C	TS-4	64	-
		TS_{-TEC}	-	55
Case4	TS-2 Failure; TS-3 Failure; Pump Stops Heat Load: $Heaters_{\_HP}$ = 75W; Peltiers = 100W $T_{initial}$ = 31°C	TS-2	65	-
Case5	Normal operation Heat Load: $Heaters_{\_HP}$ = 37.5W; Peltiers = 50W $T_{initial}$ = 20°C T_{CO2} = 20°C	No TS switches	31 (Steady-State)	28 (Steady-State)

As shown in Table 9-1, TS-1 can be skipped since all the other 3 TSs along AHP can protect the AHP from over heated. So the TS location shown in Section 4.3 is feasible.

10. CONCLUSIONS

Based on the analysis above, with the TS locations shown in Figure 4-4 and the electronic schematic shown in Figure 4-5, the Accumulator-AHP-TS temperature control system can keep the AHP and the TTCS Accumulator below their respective MDT (Maximum Design Temperatures) even in two-fault failure. As both systems are two-phase systems the MDT's define the MDP's.

Maximum accumulator heat pipe temperature is +85 ºC which is < +89 ºC (MDT) defining the MDP on 50.2 bar.
Worst case is a failing (non conducting heat pipe) and a a failing thermostat with both accumulator heat pipe control heaters fully powered. Switch off of heat load is done by neighbouring switch.

The absolute maximum temperature on the accumulator structure is +55 ºC which is in line with the safety approach (RD-8). The accumulator volume temperature requirement is ≤+55 ºC. The average temperature of the accumulator volume is even well below the TS switching temperature of 45 ºC. This gives an additional margin for the MDP analysis.

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